Historical Evidence concerning the Sun: Interpretation of Sunspot Records during the Telescopic and Pretelescopic Eras

F. R. Stephenson

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Historical evidence concerning the Sun: interpretation of sunspot records during the telescopic and pretelescopic eras

By F. R. Stephenson

Department of Physics, University of Durham, South Road, Durham DH1 3LE, U.K.

The value of sunspot observations in investigating solar activity trends – mainly on the centennial to millennial timescale – is considered in some detail. It is shown that although observations made since the mid-eighteenth century are in general very reliable indicators of solar activity, older data are of dubious quality and utility. The sunspot record in both the pretelescopic and early telescopic periods appears to be confused by serious data artefacts.

1. Introduction

The main theme of this paper is the investigation of long-term trends in solar activity on the centennial to millennial timescale. In principle, these trends may be inferred from observations of both sunspots and auroras, reports of which extend back more than two millennia. However, for reasons given immediately below, only sunspot data is considered in detail here.

Unlike auroras, sunspots provide a *direct* indication of solar activity. Almost daily reports of the number of spots visible on the Sun's disc have been compiled since early in the nineteenth century, whereas even as far back as A.D. 1750 fairly consistent observations are still preserved (McKinnon 1987).

By using this material, solar activity can be studied in detail over the last 240 years. Before 1750, the extant sunspot record becomes progressively poorer and, in particular, relatively few observations survive from the seventeenth century. Not surprisingly, pretelescopic data are even more incomplete. Hence it is in these earlier times that alternative information would be most valuable.

Although numerous reports of the aurora borealis are available, especially in recent centuries, the solar signal is only weakly preserved in the auroral record. Since about A.D. 1700, this is largely a consequence of the biased distribution over the Earth's surface of the majority of observers. Most accounts of auroras after this date originate from regions in fairly high geomagnetic latitude (especially Northern Europe and, latterly, North America); there are relatively few from more southerly zones. Auroras visible at high latitudes are mainly produced by charged particles of rather low energy; these particles are expelled from the Sun in solar wind streams that originate in coronal holes. Because coronal holes may develop at all phases of the solar cycle with comparable frequency, the more recent auroral record is not expected to show a good correlation with solar activity.

The limited utility of even modern auroral observations in studying solar activity is well exemplified by the work of Siscoe (1980). He investigated the frequency with which auroras were observed during the past 100 years at three separate sites. These locations, two in the U.S.A. and one in Germany, were all in much the same geomagnetic latitude. Siscoe found only dubious evidence for the existence of the solar cycle from the observations reported at any one station; in order to reveal the cycle clearly it was necessary to combine data from all three places. In view of the poorer consistency of the older records, there seems little hope of using auroral observations to trace the solar cycle further into the past in any detail.

In lower geomagnetic latitudes (e.g. China), most displays of the aurora borealis are produced by energetic particles that are expelled from the Sun during solar flares. Hence, had auroral data from these regions been more complete, they might have been expected to show a useful correlation with the solar cycle. As it happens, the auroral record from China and elsewhere in East Asia (mainly Japan and Korea) during the past few centuries is far from systematic. Hence its value as an index of solar activity is probably minimal.

In principle, auroral data should have greater value during the pretelescopic period for in general they are considerably more numerous than sunspots sightings. The higher incidence of observations of auroras in these early times is hardly surprising because these phenomena are often rather spectacular; on the contrary, the detection of sunspots with the unaided eye is a relatively esoteric pursuit. Some 2000 accounts of auroras are extant from before A.D. 1600, fully an order of magnitude greater than the surviving number of sunspot reports. Of these auroral records, the vast majority originate from only two areas of the globe: Europe and East Asia. The contribution from each source will be discussed in turn.

Roughly half of the auroral data before A.D. 1600 are from Europe. These have been carefully catalogued by Link (1962). The early European record of auroras appears likely to show little indication of variation in solar activity both because of (i) the relatively high geomagnetic latitude of the places of observation, as already discussed, and (ii) the sporadic nature of most auroral sightings. Few astronomical records of any kind are preserved from ancient Europe. Although the degree of preservation from medieval times is much higher, most observations of celestial phenomena were then made on a casual basis. Observers tended to have no more than a superficial interest in astronomy and noted only the more spectacular occurrences (e.g. comets, eclipses and meteor showers, as well as auroras). Reports of these events are usually cited in chronicles of towns and monasteries, rather than in works devoted to astronomy.

During ancient and medieval times, the more consistent oriental auroral record might be expected to prove superior to that from Europe for investigating past trends in solar variability. As well as the advantage of lower geomagnetic latitudes for the places of observation, most sightings in East Asia were made by official astronomers who tended to keep a fairly regular watch of the sky. However, there are still interpretational problems. Whereas historical accounts of sunspots are usually readily recognizable, the unambiguous identification of many of the descriptions of possible auroras is difficult. For example, numerous instances of reddening of the night sky are reported in sixteenth- (and also early seventeenth-) century Korean history. Although these reports would seem to relate to the aurora borealis, the frequency of occurrence is sometimes as much as two orders of magnitude greater than the expected auroral frequency (Stephenson 1988). Difficulties such as these need to be satisfactorily resolved before an objective investigation of the relevance of East Asian auroral data to the question of solar variability can be attempted.

Even if the early oriental record of auroras could be adequately purged of false sightings, it is doubtful whether at present useful corrections could be made to the observed frequency of auroral displays to allow for long-term changes in the terrestrial magnetic field. The rate of occurrence of auroras at any particular location is strongly dependent both on the intensity of the Earth's magnetic field and the position of the geomagnetic pole of the time. Although variations of the terrestrial magnetic field in recent centuries are fairly well mapped, changes on the millennial timescale are currently only poorly determined (Tarling 1988).

In the study of past solar variability, observations of sunspots thus possess a number of distinct advantages over auroral sightings. Nevertheless, the incompleteness of the sunspot record before A.D. 1750 has already been emphasized. Because regular monitoring of the Sun for spots was not maintained before 1750, any evidence for long-term trends in solar activity is likely to be contaminated by data artefacts. No more than about 160 reports of sunspots are known to have survived from the entire pretelescopic period. As several careful literature searches for ancient and medieval sunspot observations have been made in recent years (see §2), it seems unlikely that this number will be improved upon significantly by future work. With only about one reported sighting per decade, the value of pretelescopic sunspot data is obviously severely limited. Nevertheless, it is important to try to make an objective assessment of the utility of this unique record.

2. SOLAR ACTIVITY DURING THE TELESCOPIC PERIOD AS DEDUCED FROM SUNSPOT RECORDS

As discussed most recently by McKinnon (1987), solar activity during the past 170 years can be studied in detail by using the almost daily record of sunspot numbers that is available throughout that time. A systematic watch of the Sun for spots was initiated in 1849 by the Swiss astronomer Rudolph Wolf and the scheme that he devised for estimating sunspot numbers is still use in today. Much of what is known regarding solar activity in the earlier part of the telescopic period is also a consequence of the pioneering researches of Wolf. As the result of an extensive search of European literature (scientific journals and observatory archives), Wolf was able to construct a fairly complete sequence of daily sunspot numbers as far back as 1818. These data, edited by Waldmeier (1961), are fully tabulated by McKinnon (1987). There are only a few gaps lasting for more than a week in the whole of the sunspot record between 1818 and 1848, except for the years 1820, 1825 and 1835, which are rather less well represented. Between 1749 and 1817 the data were of inferior quality, but Wolf was still able to derive monthly means.

2.1. *Solar activity since* A.D. 1715

Figure 1, which shows the smoothed monthly sunspot numbers between A.D. 1749 and 1985, is taken from McKinnon (1987). Over this period of rather less than 250 years, both the length of any particular cycle and the sunspot number at different maxima were very variable.

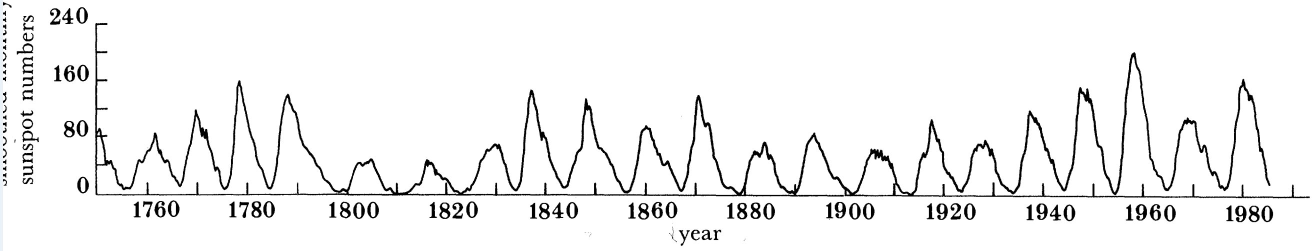

FIGURE 1. Smoothed monthly sunspot numbers: July 1749 to June 1985. (After McKinnon 1987.)

Although the mean interval between successive maxima was 10.9 years, the actual interval could be as short as 7.3 years (1829–37) or as long as 17.1 years (1788–1805). The peak sunspot number in any cycle ranged over a factor of 4: from 49 in 1805 and 1816 to 201 in 1957 (overall mean 116.1). Hence despite the fact that the sunspot cycle is a remarkably persistent feature of solar behaviour, it is obviously no more than quasi-regular. Recently, Weiss (1988) has argued that the aperiodic behaviour of the solar cycle is an example of deterministic chaos.

Although solar activity in the period since A.D. 1749 is fairly well determined, the situation before that date is less encouraging. Using historical records, Wolf deduced annual mean sunspot numbers between 1700 and 1749, but previous to 1700 he made no attempt to deduce even annual means. Since the efforts of Wolf roughly 150 years ago, no systematic literature search has been made to improve on his results for the period between about 1715 and 1817, an undertaking that would certainly seem desirable today.

2.2. *The Maunder Minimum*

For the period between A.D. 1610 and 1715, Eddy (1976) made a revised compilation of European sunspot records from a variety of sources. He also incorporated Wolf's original data. Eddy used these observations to estimate annual mean sunspot numbers during the period in question, but especially before 1650 his information was very fragmentary.

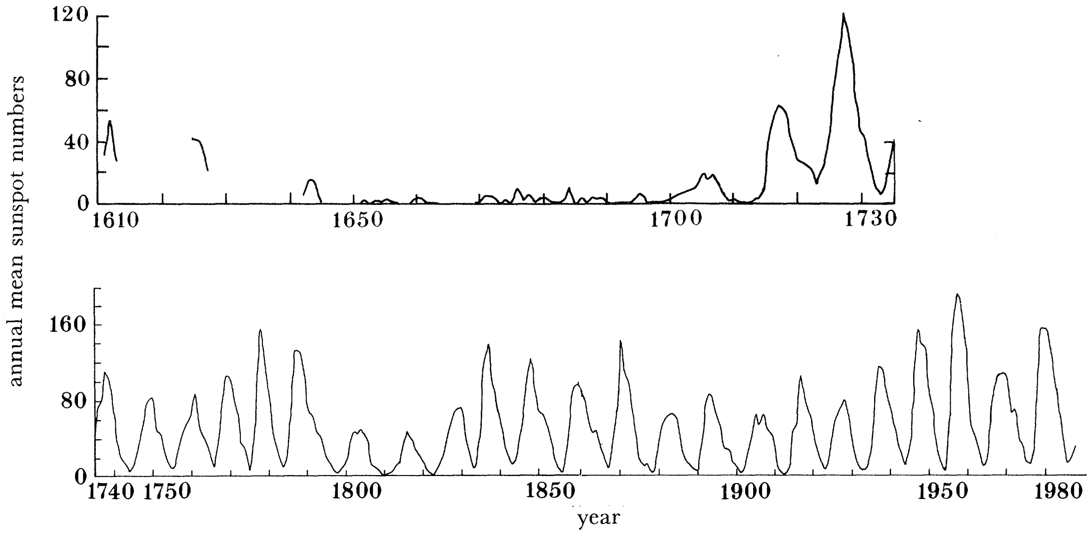

FIGURE 2. Annual mean sunspot numbers: A.D. 1610–1988 (J. A. Eddy, personal communication).

Figure 2, which shows derived annual mean sunspot numbers from A.D. 1610 to 1988, is due to Eddy (personal communication). It is apparent from this diagram that although the sunspot cycle has been clearly evident since A.D. 1715, it cannot be traced in the previous century. In particular, the level of solar activity over the entire interval between about A.D. 1645 and 1715 (the 'Maunder Minimum') would appear to have been considerably depressed relative to that in more recent centuries. There can be little doubt that during much of the Maunder Minimum the Sun was unusually quiet. Thus Eddy (1976) noted that astronomers of the time, such as Cassini and Flamsteed, had commented on the scarcity of sunspots over many years.

However, for a variety of reasons, it is very difficult to quantify the level of solar activity with any confidence during the Maunder Minimum. Factors that might be mentioned include the following: (i) the poor quality of telescope optics at this early period, so that only larger sunspots would be noticed; (ii) the lack of systematic observations of the Sun until much later; and (iii) the relative inaccessibility of astronomical records of any kind from most of the seventeenth century compared with in more recent times. The establishment of the official journals of the Royal Societies of London and Paris in the late seventeenth century did much to encourage the dissemination of reports of celestial phenomena.

2.3. *Comparison data: occultations of stars by the Moon*

To illustrate the difficulties in interpreting the early telescopic sunspot record, it is helpful to investigate the changing annual frequency with which some other kind of astronomical phenomenon is reported during the same period. A useful comparison is provided by occultations of stars by the Moon; detailed catalogues of these events have been compiled in recent years. Although occultations represent a completely independent phenomenon to sunspots, they were often observed by the same astronomers and are recorded in much the same literature. To some extent, the frequency with which early observations of occultations are still preserved today thus seems likely to be affected by similar factors to those pertaining to sunspot records. However, although the observed occultation frequency might be expected to show evidence of short-term periodicity (related to the 18-year regression of the lunar nodes), no significant long-term cyclical behaviour is expected, in marked contrast to sunspots.

Since the early seventeenth century, astronomers have measured the time of occurrence of occultations on account of the value of such data in improving knowledge of the lunar motion. The most recent and extensive catalogue of these data is that of Morrison *et al.* (1981). Covering the period from A.D. 1623 to 1942, this compilation contains some 40000 individual timings. Details for nearly 3000 separate observations between 1623 and 1860, virtually all from Europe, are printed in the above work. However, the quantity of later measurements is so vast that these are listed in microfiche. Here I concentrate on the earlier set of data.

The number of separate occultations recorded in the selected period of 238 years, although large, is substantially less than 3000. Many astronomers timed both the beginning and end of an occultation of the same star and Morrison *et al.* listed these as distinct events. Further, the same occultation would frequently be reported independently by several observers, particularly if the star were bright or a member of a well-known group such as the Pleiades. In enumerating the annual frequency of recorded occultations between 1623 and 1860 I have thus counted only one occultation of any given star per night. In this way the occultation record will have a closer parallel to that for sunspots. The total number of individual occultations reported up to 1860 is about 1300.

In figure 3 is plotted the annual frequency of occultation observations (with the restrictions discussed above) between 1623 and 1860. The diagram reveals clear indication of cyclical behaviour of approximate period 9 years (half the nodal regression) in the later record; this arises from the very uneven distribution of stars in the ecliptic zone. Before about 1800, evidence for such periodicity is confused by other factors: largely data artefacts due to the lack of any regular observing programme and relative inaccessibility of observational reports.

The main longer-term features of figure 3 are (i) very few preserved data before 1670 (a total of no more than 30 observations since the beginning of the telescopic era); (ii) a significant

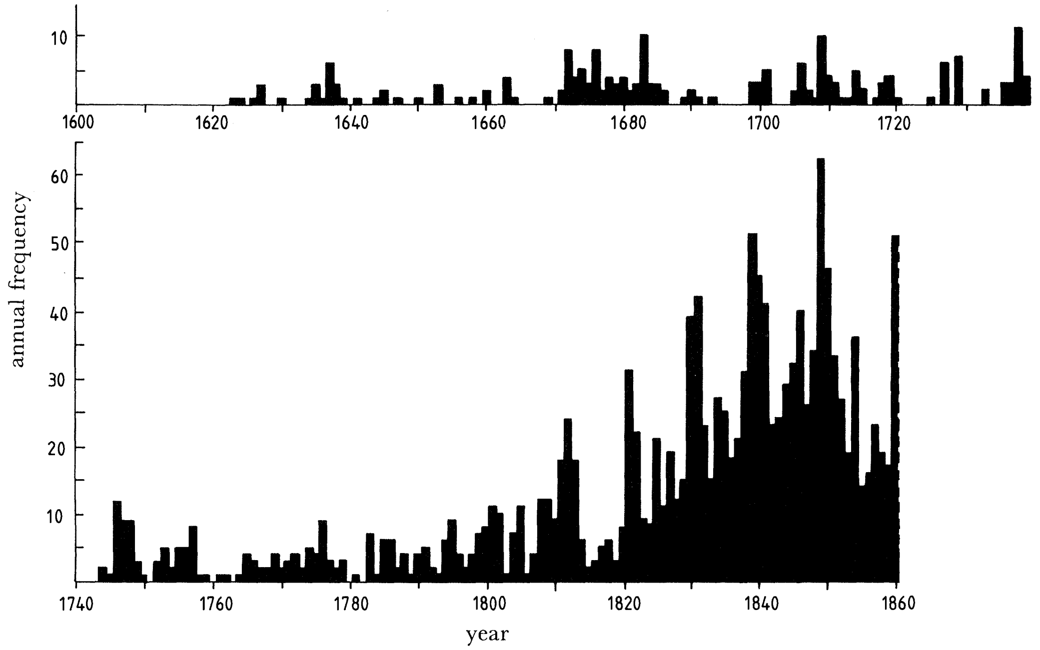

FIGURE 3. Annual frequency of reports of occultations of stars by the Moon observed telescopically: A.D. 1623–1860.

increase in the mean annual frequency of recorded observations around 1670 with little further change until 1810; (iii) a sharp rise in annual frequency at 1810 followed by still further growth in the remaining 50 years of the selected interval. Investigation of the typical brightness of the occulted stars at different epochs between 1623 and 1860 does not reveal a marked trend towards observation of fainter stars in more recent times. Hence improvement in telescope optics was only partly responsible for the observed long-term features in figure 3. Evidently only a small and quite variable proportion of the observable events was actually witnessed or recorded or both during the eighteenth century, whereas in the seventeenth century the situation was even worse.

2.4. *Interpretation of the early telescopic sunspot record*

The results of the above investigation can be applied in a general way to the interpretation of early sunspot data. Comparing figure 2 with figure 3, it seems very likely that the preserved sunspot record from the earlier telescopic period may also be affected by significant trends of a spurious nature. In particular, observations of sunspots made during the seventeenth century were possibly too infrequent to reveal evidence of the solar cycle. It is also probable that recent estimates of the mean level of solar activity during the Maunder Minimum, e.g. as displayed in figure 2, may be too low by a large (and appreciably time-variant) factor. Summarizing, although the sunspot record since 1818, and probably since 1749, is a reliable indicator of solar activity, earlier observations are of very limited value. Especially during the seventeenth century, it seems more reasonable to infer long-term changes in solar activity from the available proxy records such as ^{14}C and ^{10}Be (Eddy 1988).

3. The pretelescopic sunspot record (*ca.* 150 b.c. to a.d. 1610)

Pretelescopic records of sunspots are preserved from only three regions of the world: (i) East Asia (almost exclusively China and Korea); (ii) Europe; and (iii) the Arab dominions. The contribution from sources (ii) and (iii) is virtually negligible compared with that from (i). For instance, the detailed catalogue of unaided-eye sunspot observations by Wittmann & Xu (1987), which contains fairly complete entries from both oriental and occidental history, cites less than 10 individual observations from outside East Asia during the entire period anterior to the invention of the telescope.

3.1. *Babylonian texts*

Although the surviving Late Babylonian astronomical diaries are extremely detailed (Sachs & Hunger 1988), they contain no recognizable allusions to sunspots. This circumstance may be at least partly a result of the Babylonians' concern with observing regular and thus predictable phenomena. Eclipses or lunar and planetary movements are recorded in abundance, but references to sporadic events (e.g. auroras and meteor showers) are rare. Nevertheless, it should be emphasized that no more than about 5% of the original texts have survived, with possible loss of key records.

3.2. *European and Arab records*

In ancient and medieval Europe, the aristotelian notion of a faultless Sun probably contributed to what appears to be an almost complete lack of interest in observing sunspots. Nevertheless, it is likely there are additional explanations for the small number of sunspots preserved in European history during this period. Because very few writings of an astronomical nature have survived from before the Renaissance, some sunspot records may well have been lost. Ptolemy's *Almagest* is unique among surviving ancient European works in quoting a variety of celestial observations: notably, eclipses and lunar and planetary phenomena. However, in this rather specialized treatise, sightings of sunspots and other seemingly random occurrences (e.g. new stars or meteor showers) would have no place.

As noted in the Introduction to this paper, most allusions to celestial phenomena from Europe in ancient and medieval times are recorded in chronicles and other historical works. These compilations often make reference to the more spectacular celestial events. However, because the observers had, in general, little interest in astronomy, they may have hardly ever noticed minor phenomena such as sunspots. In this context, it is perhaps significant that two of the very few sunspot observations made in Europe during medieval times (in a.d. 1365 and 1371) took place when smoke from forest fires dimmed the Sun sufficiently for it to be viewed directly (Vyssotsky 1949).

Medieval Arab astronomers tended to explain sunspots in terms of transits of Venus or Mercury across the solar disc. Several such instances are on record: in a.d. 840, *ca.* 1030, 1068 and *ca.* 1130. These observations have been discussed in detail by (Goldstein 1969). In practice, Venus (unlike Mercury) is quite visible to the unaided eye when silhouetted against the Sun's disc, as was true at the last transit in 1882. However, by reference to the calculations of Meeus (1958), Goldstein was able to show that no suitable transits occurred in or near the stated years; hence the observers must have witnessed sunspots instead. Attempts by the Arab astronomers to interpret sunspots as planetary transits may have been partly because of their familiarity with Aristotle's hypothesis of a blemish-free Sun. Nevertheless, they were obviously fully aware that the inner planets (like the Moon) could pass directly in front of the Sun. The appearance of sunspots would thus seem to the observers to provide 'proof' that these planets could actually be seen in silhouette on the solar disc.

There is, in fact no evidence that a Venus transit was ever observed before the introduction of the telescope. Recently (Stephenson 1990), I compared Meeus's (1958) list of computed dates for Venus transits with the dates of pretelescopic sunspot sightings (mainly from East Asia) compiled by Wittmann & Xu (1987) and Yau & Stephenson (1988). There proved to be no coincidences or near-coincidences. Hence it may be concluded that Jeremiah Horrocks still holds the distinction of making the first known observation of a transit of Venus. This observation took place in 1639, following a successful prediction by Horrocks of the event.

3.3. *Oriental observations*

In the remainder of this section, I concentrate on East Asian sunspot sightings. These comprise some 95% of all pretelescopic sunspot reports. A pioneering study of Far Eastern observations of sunspots was made by Kanda more than 50 years ago (Kanda 1933). More recently (some ten years ago), several further contributions to the subject were published; among the more detailed investigations were those by the Yunnan Observatory (1976), Clark & Stephenson (1978) and Chen & Dai (1982). Following the publication during the last two years of revised catalogues of unaided-eye sunspot sightings by Wittmann & Xu (1987) and Yau & Stephenson (1988), it is appropriate to reconsider just what the early observations are capable of revealing with regard to past trends in solar activity. The latter paper, referred to subsequently as Y.S., forms the basis of much of the succeeding discussion.

Apart from slight differences in translation, most of the entries in the catalogue of Wittmann & Xu are identical with those listed by Y.S. However, the former paper is concerned with both oriental and occidental sightings whereas the latter work is restricted to observations from East Asia. In addition, Y.S. correct a few minor errors in the compilation of Wittmann & Xu and also include several additional observations in the pretelescopic period. Both catalogues contain oriental sightings made after the invention of the telescope, the compilation of Y.S. extending down to as late as 1918. Nevertheless, it is probable that all of these more recent observations were made with the unaided eye; as an astronomical device, the telescope made little impact throughout East Asia until the present century. The number of reported sightings of sunspots in the Orient since A.D. 1610 (65) is minute compared with the number of telescopic observations made in the West. For example, as many as 750 reports of sunspots are preserved from Europe during the Maunder Minimum alone. Hence the value of these more recent naked-eye data is severely limited in the study of past solar variability. In this section I thus restrict attention to those observations made before the telescopic era.

The entries in the catalogues of Wittmann & Xu and Y.S. are based entirely on *written* records. It is regrettable that apart from a few highly schematic illustrations, drawings of sunspots from the pretelescopic era are extremely rare. Accounts of sunspots are mainly cited in astronomical treatises; these form important sections of the official dynastic histories of China and Korea. Numerous celestial observations of all kinds (eclipses, lunar and planetary movements, comets, novae and supernovae, meteor showers and auroras, as well as sunspots) are found in these treatises. Such data are largely summaries of the reports of the court astronomers, whose task it was (at least in principle) to maintain a regular watch of both the day and night sky. Throughout East Asia the prime motive for celestial observation was astrological. Even in recent centuries, astronomers still closely followed the traditions established in ancient China. Thus the terminology used to describe celestial phenomena remained almost unchanged over two millennia.

Although the earliest reliable report of a sunspot from the Orient dates from 165 B.C., relatively few accounts have survived before A.D. 300. With a single exception (an observation made in Japan in A.D. 851), all Far Eastern sunspot records earlier than A.D. 1150 are from China. After that date there is a sizeable contribution from Korea, but Chinese observations still tend to dominate. Very occasionally a report from Vietnam is also encountered (in A.D. 1276, 1593 and 1603).

Most oriental sunspot records follow only two basic forms: (i) 'Within the Sun there was a black spot' (*hei-tzu*); and (ii) 'Within the Sun there was a black vapour' (*hei-ch'i*). Entries of the former type are only found after A.D. 300; use of *hei-ch'i*, although generally rarer, occurs at all periods. The word *tzu*, rendered 'spot' in (i), has several more general meanings such as 'seeds' or 'pellets'. Hence when referring to the Sun, objects of small angular size are clearly indicated. Especially as some records state that *hei-tzu* were seen for several days within the Sun, there can be no viable alternative to a sunspot interpretation. The expression *ch'i* ('air', 'vapour', etc.) can have a variety of meteorological as well as astronomical meanings; it is the standard term to indicate auroras, whereas in the appropriate context it may be used to describe cloud formations. However, when a black vapour is specifically described as appearing 'within the Sun', a sunspot identification can be confidently assumed. As in the case of *hei-tzu*, *hei-ch'i* were from time to time seen on the Sun for several days.

Other, comparatively rare descriptions that fairly obviously relate to sunspots are miscellaneous objects appearing within the Sun, e.g. birds (especially crows) or stars. Again, these phenomena were sometimes of several days' duration. Because there is no grammatical plural in Classical Chinese (the language in which virtually all East Asian astronomical observations are recorded), it is best to assume that all sunspot reports refer to a single spot or group unless the number of objects visible is specified. Several sightings of double or multiple spots are on record, the earliest in A.D. 355 when two separate sunspots 'as large as peaches' were seen together.

3.4. *Temporal distribution of the oriental sunspot sightings*

In figure 4 is shown the decade distribution of unaided-eye oriental sunspot observations from earliest times (200 B.C.) until A.D. 1610, as listed in the catalogue of Y.S. The diagram is

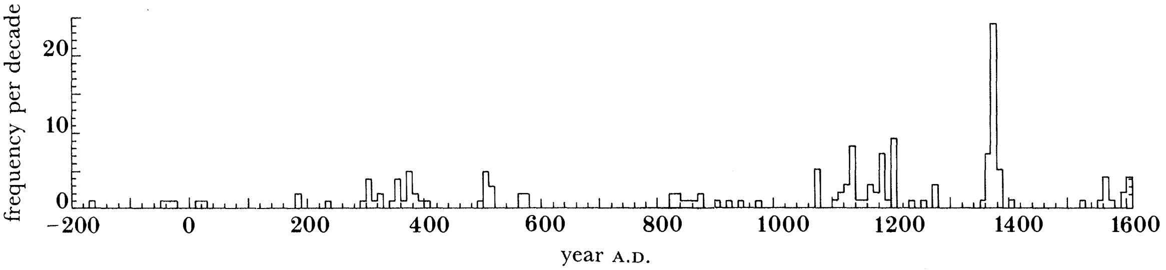

FIGURE 4. Decade distribution of unaided-eye sunspot observations recorded in East Asia: 165 B.C. to A.D. 1610. (After Yau 1988*b*.)

taken from a corresponding figure in the paper by Yau (1988*b*). In all, 157 separate occurrences of sunspots are represented. The individual totals are 122 from China, 34 from Korea, three from Vietnam and one from Japan. Owing to three instances when the same spot (or spot group) was observed in both China and Korea, the sum total is 160 rather than 157.

The main features of figure 4 may be summarized as follows: (i) only sporadic sightings of sunspots before about A.D. 1100; (ii) comparatively frequent observations both in China and Korea during the twelfth century of our era; (iii) very few spots noted between about A.D. 1200 and 1360; (iv) a marked peak around 1370, mainly resulting from an excess of Chinese records; (v) few subsequent references to sunspots in either Chinese or Korean history until the end of the period covered by the diagram. If interpreted literally, the oriental sunspot record would thus imply a number of lengthy intervals when the Sun was quiet, interspersed with active periods lasting up to about a century. However, although the existence of the sunspot cycle can be detected from pretelescopic observations (Wittmann & Xu 1988; Yau 1988*b*), a variety of evidence suggests that the existing record is contaminated by significant data artefacts. This evidence will be discussed below.

3.5. *Efficiency of the oriental observers*

Judging from the fact that almost every apparition of Halley's Comet since 240 B.C. is recorded in oriental history (Stephenson & Yau 1986), it might be inferred that during ancient and medieval times the astronomers of East Asia were remarkably efficient observers. (Compared with some long-period comets, Halley's Comet is not particularly brilliant even when passing fairly close to the Earth.) However, as will be discussed below, there is good evidence that the astronomers were far from systematic observers of most phenomena. This remark is especially true of sunspots. Reference to figure 4 shows that with a single notable exception, the peak number of sunspots (or spot groups) reported in any one decade during the whole of the pretelescopic period was less than 10. (Between A.D. 1367 and 1376, as many as 28 sunspots were sighted, half of them within a period of two years.) Obviously, only large sunspots are visible to the unaided eye, but until recently it has not been possible to make an objective assessment of the efficiency of the oriental observers in noting spots. Fortunately, a systematic survey of the Sun made without a telescope by Mossmann (1989) around the time of the last solar maximum now provides valuable comparison data.

Over an interval of 13 months between 1981 and 1982, Mossmann detected sunspots without any optical aid on 50 separate occasions; using a filter this number increased to 170 observations. In reviewing the results of this project, Eddy *et al.* (1989) estimated that Mossman's rate of sighting sunspots with the unaided eye, when adjusted for cycle phase, is as much as 200 times the long-term rate from the Orient. Even when compared with the unusual achievement of the Chinese and Korean astronomers around A.D. 1370, Mossman was still an order of magnitude more successful. Overall, in reporting sunspots visible to the unaided eye, the astronomers of East Asia evidently achieved an efficiency of less than 1%.

Mossman's remarkable success at detecting sunspots without any optical aid suggests that there is no need to assume that the early oriental astronomers were in the habit of using some kind of optical filter to dim the Sun when looking for spots. This conclusion is confirmed by the East Asian records themselves. Thus several accounts mention that the Sun was unusually dull, or appeared yellow or red, when sunspots were sighted; other reports imply observation close to sunrise or sunset. Willis *et al.* (1988) showed that fully 40% of all pretelescopic sightings of sunspots from the Orient were made in the two months March and April. At these times, dust storms are prevalent in East Asia. Airborne dust would act as a natural filter, reducing the solar glare and enabling sunspots to be more readily perceived.

The figure of 157 pretelescopic sunspot sightings in East Asian history, rather than the many thousands that might be expected, may in part be explained by emphasis on reporting only the very largest visible sunspots (or spot groups) by the oriental astronomers. For example, some 10 sunspot groups were recorded as having an obviously non-circular shape. However, large spot groups tend to be common around a solar maximum and even during the short time-span of his survey Mossman was able to detect several elementary shapes. In general it would seem that the Sun was only infrequently scrutinized for spots by the East Asian astronomers. Furthermore, of the observations actually made, few were presumably considered to be worth citing in the official histories (Eddy *et al.* 1989).

3.6. *Uniformity of the oriental record*

Of the various gaps evident in figure 4, there can be little doubt that the lacuna between about A.D. 600 and 800 is largely artificial in origin. Large numbers of records, both astronomical and otherwise, were destroyed when the rebel Chinese general An Lu-shan sacked the T'ang Dynasty capital of Ch'ang-an in A.D. 755. Much important material was probably lost at other periods; most of the various capitals that have served China throughout its long history have been extensively looted at one time or another, e.g. during the violence which usually accompanied the fall of a dynasty.

Changing attitudes towards celestial portents was probably a major factor in complicating the existing record of sunspots as well as of other celestial phenomena. Thus it is interesting to note that more than half of all Chinese sightings of sunspots during the pretelescopic period are reported during the reigns of only six emperors. (In all, some 150 emperors ruled China in the 1800 years covered by figure 4.) In this connection, Park (1977) had made a detailed study of the various portants (celestial and otherwise) reported in Korean history. He noted that Buddhist rulers were in general more gullible with regard to omens than Confucians; the latter tended to adopt a more rational view of portents. One king (Yonsan, who reigned between A.D. 1495 and 1506) was so hostile towards portentology that he actually abolished the time-honoured Office of Astronomy. However, this was soon reinstated by his successor.

Park cites an interesting case from A.D. 1204. In February of that year a sunspot was observed for three days in Korea. The Astronomer Royal of the time tried to suppress the report because he knew from Chinese history that a similar occurrence had presaged an emperor's death. Nevertheless, the portent was duly registered. A month later the Korean king died. After this event, there are no further mentions of sunspots in Korean history for 54 years, although several sightings were made in China during the intervening time. Only when a subsequent king (Kojong) had been on the throne for 45 years was it apparently considered safe for the Korean astronomers to report another sunspot. Just how much the long-term sunspot record from both Korea and China is similarly affected is impossible to judge, but it seems likely that the influence of astrology was far from negligible.

Park found marked changes in the relative importance of different omens at various periods. For example, there was a notable surge in recording solar haloes and sightings of Venus in daylight around A.D. 1400 because at the time they seemed to be threatening the intrinsic brightness of the Sun (the symbol of the king). By contrast, interest in reporting meteors and night-time observations of the planets waned simultaneously. No similarly detailed study has been made of portentology throughout Chinese history, but it seems likely that imperial attitudes to omens were also extremely fluid.

Figure 5 illustrates just how variable the record of astronomical phenomena during even a single dynasty can be. This diagram, produced at my suggestion by my colleague K. K. C. Yau (Yau 1988*a*), is a plot of the annual frequency of astronomical events of all kinds (comets, eclipses, lunar and planetary conjunctions, sightings of Venus in daylight, meteor showers, auroras, etc.) recorded in Korea during the Koryo Dynasty (A.D. 918–1392). Most of the events noted by the Korean astronomers would be expected to show no obvious trends in frequency on timescales much longer than a decade. Hence the extremely complex pattern visible in figure 5 must be largely of artificial origin. Figure 6 represents the results of a similar investigation for China, but this covers many dynasties. This diagram is based on a decade-by-decade count of celestial phenomena of all types recorded in Chinese history between 200 B.C. and A.D. 1610 (Yau 1988*a*). Once again, most of the highly irregular distribution must be of historical rather than astronomical origin.

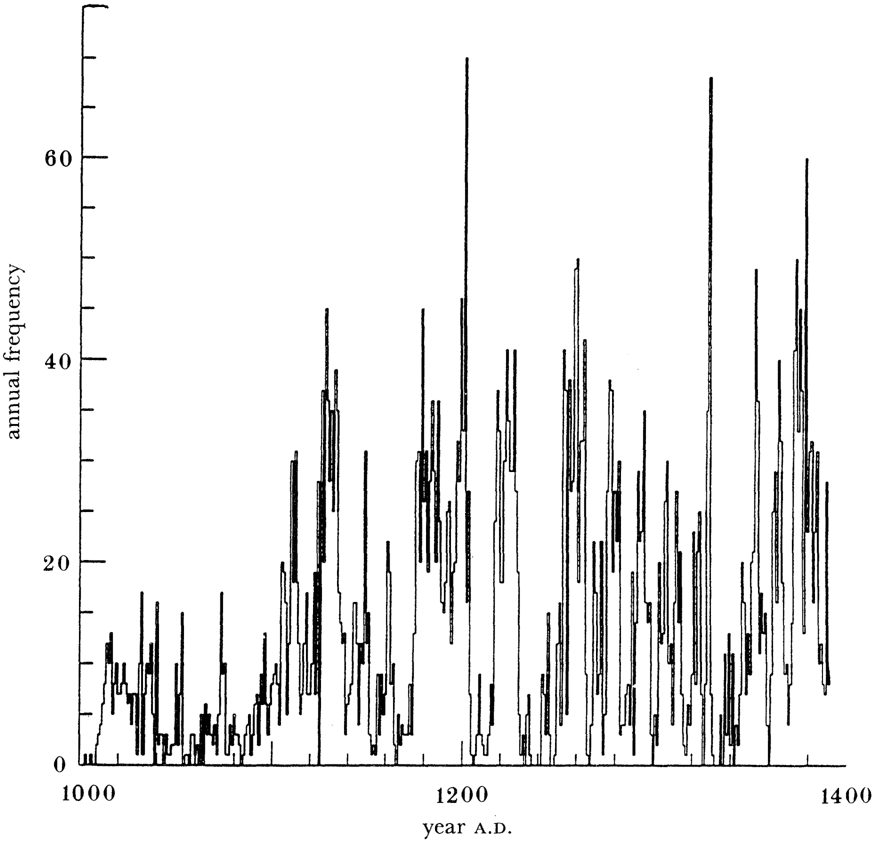

FIGURE 5. Annual frequency of astronomical observations of all kinds recorded in Korea during the Koryo Dynasty (A.D. 918–1392). (After Yau 1988*a*.)

3.7. *Interpretation of the oriental sunspot record*

In attempting to assess the relevance of the oriental record of sunspot sightings to the study of long-term trends in solar variability it is helpful to consider the changing frequency with which some other solar phenomenon is reported in East Asian history. Solar haloes, although

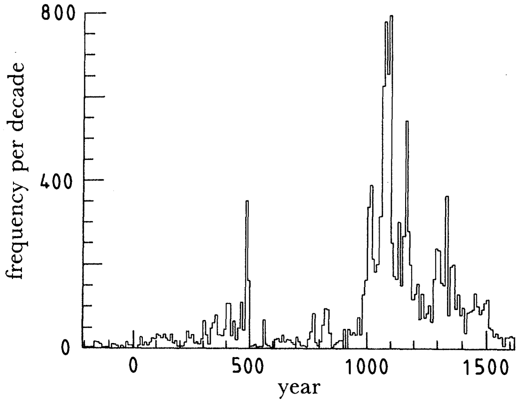

FIGURE 6. Decade distribution of astronomical observations of all kinds recorded in China: 200 B.C. to A.D. 1610. (After Yau 1988*a*.)

purely atmospheric phenomena, are often recorded in the same sections of dynastic histories as sunspots. Neither phenomenon was, of course, understood by the oriental astronomers and both are often listed under the heading of 'solar changes'. Haloes provide a particularly useful comparison because they are reported with comparable frequency to sunspots.

Figure 7 is a plot of the decade-by-decade frequency of solar haloes recorded in Chinese history from the beginning of the Christian era to A.D. 1610. This is taken from the paper by Yau (1988*b*). The diagram reveals marked variation in the numbers of haloes noted per decade, ranging from zero for lengthy periods to almost 20. Systematic observation of the sky would be expected to reveal many more haloes and once again we have a very incomplete record. Much of the pattern visible in figure 7 is thus likely to be of artificial rather than atmospheric origin, reflecting both changes in attitudes to celestial portents and varying degrees of preservation of observer's reports. Many of the main features of figure 7 show a fairly good correlation with those of figure 4, peaks occurring around A.D. 400, 1200 and 1400, and troughs around A.D. 700, 1000 and 1300. This suggests that many of the long-term variations present in the sunspot record are spurious, as implied by much of the discussion in the earlier part of this section.

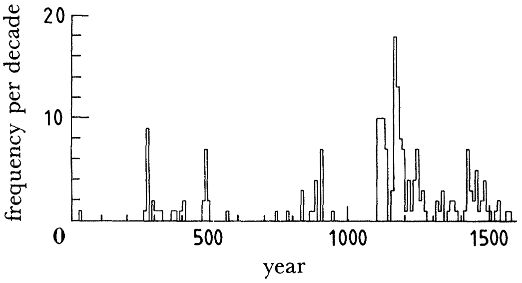

FIGURE 7. Decade distribution of solar haloes recorded in Chinese history from the beginning of the Christian era to A.D. 1649. (After Yau 1988*b*.)

4. CONCLUSIONS

Two main conclusions may be deduced from the foregoing investigation of sunspot observations. (i) In the case of the more recent data (from A.D. 1750 and especially since 1818) important results can be obtained regarding past solar variability. The roughly decadal cycle of solar activity can be mapped on a fairly systematic basis throughout the whole of the last 240 years. During this same interval, long-term trends on the centennial timescale (the so-called Gleissberg cycle) are also apparent. (ii) The solar cycle can in fact be traced as far back as about A.D. 1715 and it is possible to detect its existence even during the pretelescopic period. However, at any time anterior to about 1715, evidence for the existence of long-term trends in solar activity must be regarded as ambiguous. Studies of solar activity before about A.D. 1715 are thus best based on proxy records such as ^{14}C in tree-rings or ^{10}Be in ice cores.

Although many of the arguments presented in this paper might appear to be negative, the aim throughout has been to attempt an objective interpretation of the available sunspot data. It is unfortunate that the excellent series of observations available in more recent centuries is not preceded by data of comparable quality.

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REFERENCES

Chen Mei-dong & Dai Nian-zu 1982 *Stud. Hist. nat. Sci.* **1**, 227.

Clark, D. H. & Stephenson, F. R. 1978 *Q. Jl R. astr. Soc.* **19**, 387.

Eddy, J. A. 1976 *Science, Wash.* **192**, 1189.

Eddy, J. A. 1988 In *Secular solar and geomagnetic variations in the last 10000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 1–23. Dordrecht: Kluwer.

Eddy, J. A., Stephenson, F. R. & Yau, K. K. C. 1989 *Q. Jl R. astr. Soc.* **30**, 65.

Goldstein, B. R. 1969 *Centaurus* **14**, 49.

Kanda Shigeru 1933 *Proc. imp. Acad. Japan* **9**, 23.

Link, F. 1962 *Geofyz. Sb.* **10**, 297.

McKinnon, J. 1987 *World Data Center A for Solar–Terrestrial Physics, Boulder, Colorado. Report UAG*-95.

Meeus, J. 1958 *J. Br. astr. Ass.* **68**, 98.

Morrison, L. V., Lukac, M. R. & Stephenson, F. R. 1981 *Royal Greenwich Observatory Bull.* 186.

Mossman, J. E. 1989 *Q. Jl R. astr. Soc.* **30**, 59.

Park Seong Rae 1977 Portents and politics in early Yi Korea: 1392–1519. Ph.D. thesis, University of Hawaii, U.S.A.

Sachs, A. J. & Hunger, H. 1988 *Astronomical diaries and related texts from Babylonia*, vol. I. Wien: Osterreichischen Akademie der Wissenschaften.

Siscoe, G. L. 1980 *Rev. Geophys. Space Phys.* **18**, 647.

Stephenson, F. R. 1988 In *Solar–terrestrial relationships and the Earth environment in the last millennia* (ed. G. Cini Castagnoli), pp. 133–150. Amsterdam: North-Holland.

Stephenson, F. R. 1989 (In preparation.)

Stephenson, F. R. & Yau, K. K. C. 1986 *J. Br. interplanet. Soc.* **38**, 195.

Tarling, D. H. 1988 In *Secular solar and geomagnetic variations in the last 10,000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 349–365. Dordrecht: Kluwer.

Vyssotsky, A. N. 1949 *Meddn Lunds astr. Obs.* Historical Papers, no. 22.

Waldmeier, M. 1961 *The sunspot-activity in the years 1610–1960.* Zurich: Schultess.

Weiss, N. O. 1988 In *Secular solar and geomagnetic variations in the last 10000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 69–78. Dordrecht: Kluwer.

Willis, D. M., Doidge, C. M., Hapgood, M. A., Yau, K. K. C. & Stephenson, F. R. 1988 In *Secular solar and geomagnetic variations in the last 10000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 187–202.

Wittmann, A. D. & Xu Zhentao 1987 *Astron. Astrophys. Suppl. Ser.* **70**, 83.

Wittmann, A. D. & Xu Zhentao 1988 In *Secular solar and geomagnetic variations in the last 10000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 131–139. Dordrecht: Kluwer.

Yau, K. K. C. 1988*a* An investigation of some contemporary problems in astronomy and astrophysics by way of early astronomical records. Ph.D. thesis, University of Durham, U.K.

Yau, K. K. C. 1988*b* In *Secular solar and geomagnetic variations in the last 10000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 161–185. Dordrecht: Kluwer.

Yau, K. K. C. & Stephenson, F. R. 1988 *Q. Jl R. astr. Soc.* **29**, 175.

Yunnan Observatory 1976 *Acta astr. sin.* **17**, 217. (English trans. *Chinese Astr.* **1**, 347.).